PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 7 : G06F 17/14	A1	(11) International Publication Number: WO 00/55757 (43) International Publication Date: 21 September 2000 (21.09.00)

(21) International Application Number: PCT/US00/06941

(22) International Filing Date: 17 March 2000 (17.03.00)

(30) Priority Data:
60/124,746 17 March 1999 (17.03.99) US

(71) Applicant (*for all designated States except US*): THE JOHNS HOPKINS UNIVERSITY [US/US]; 708 N. Wyman Park Center, 3400 North Charles Street, Baltimore, MD 21218-2695 (US).

(72) Inventor; and
(75) Inventor/Applicant (*for US only*): TRAN, Trac, D. [US/US]; 9716 Patuxent Lane, Laurel, MD 20723 (US).

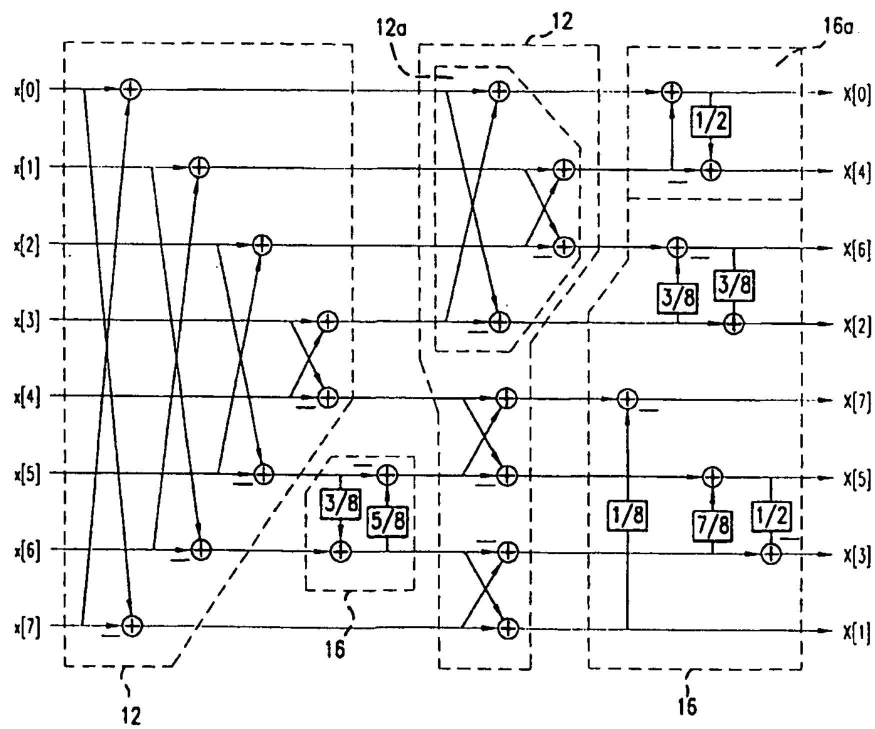
(74) Agent: OLIVER, Eric; Dickstein Shapiro Morin & Oshinsky LLP, 2101 L Street, N.W., Washington, DC 20037-1526 (US).

(81) Designated States: AE, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, DM, EE, ES, FI, GB, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: A FAST MULTIPLIERLESS TRANSFORM

(57) Abstract



A preferred embodiment of the invention provides an M x M multiplierless perfect reconstruction block transform (i.e., perfect reconstruction is realized if the invention is utilized for both analysis and synthesis, otherwise, if the invention is used on only one end, near-perfect reconstruction results) with symmetric/antisymmetric basis functions, i.e., linear phase filter. In a preferred embodiment, a cascade of ±1 butterfly stages (12) is provided followed by two invertible matrices. Each invertible matrix is made up of a cascade of lifting steps (16) and scaling factors (α_i). The scaling factors can be folded into the quantization stepsizes. A forward binDCT (e.g., for signal analysis), can be implemented using a cascade of ±1 butterflies (12) and dyadic lifting steps (16). Furthermore, an inverse binDCT (e.g., for signal synthesis can be easily realized using lifting steps (16) of reverse order and inverted polarity, cascaded with ±1 butterflies (12). In accordance with an embodiment of the invention, all of the lifting coefficients have been chosen to be dyadic rational numbers. Each dyadic lifting step can be constructed by a simple combination of shift-and-add operations.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania
AM	Armenia
AT	Austria
AU	Australia
AZ	Azerbaijan
BA	Bosnia and Herzegovina
BB	Barbados
BE	Belgium
BF	Burkina Faso
BG	Bulgaria
BJ	Benin
BR	Brazil
BY	Belarus
CA	Canada
CF	Central African Republic
CG	Congo
CH	Switzerland
CI	Côte d'Ivoire
CM	Cameroon
CN	China
CU	Cuba
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
GA	Gabon
GB	United Kingdom
GE	Georgia
GH	Ghana
GN	Guinea
GR	Greece
HU	Hungary
IE	Ireland
IL	Israel
IS	Iceland
IT	Italy
JP	Japan
KE	Kenya
KG	Kyrgyzstan
KP	Democratic People's Republic of Korea
KR	Republic of Korea
KZ	Kazakstan
LC	Saint Lucia
LI	Liechtenstein
LK	Sri Lanka
LR	Liberia
LS	Lesotho
LT	Lithuania
LU	Luxembourg
LV	Latvia
MC	Monaco
MD	Republic of Moldova
MG	Madagascar
MK	The former Yugoslav Republic of Macedonia
ML	Mali
MN	Mongolia
MR	Mauritania
MW	Malawi
MX	Mexico
NE	Niger
NL	Netherlands
NO	Norway
NZ	New Zealand
PL	Poland
PT	Portugal
RO	Romania
RU	Russian Federation
SD	Sudan
SE	Sweden
SG	Singapore
SI	Slovenia
SK	Slovakia
SN	Senegal
SZ	Swaziland
TD	Chad
TG	Togo
TJ	Tajikistan
TM	Turkmenistan
TR	Turkey
TT	Trinidad and Tobago
UA	Ukraine
UG	Uganda
US	United States of America
UZ	Uzbekistan
VN	Viet Nam
YU	Yugoslavia
ZW	Zimbabwe

A FAST MULTIPLIERLESS TRANSFORM

This application claims the benefit of U.S. Provisional Patent Application No. 60/124,746, filed on March 17, 1999, which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

Mathematical transforms (e.g., the fourier transform, the discrete cosine transform, the wavelet transform, etc.) have found application in signal processing computer algorithms, particularly the compression and coding of speech, audio, image and video data. Such transforms are used in the currently popular image compression standard referred to as "JPEG" developed by the Joint Photographic Experts Group, as well as in high-performance video coding standards such as MPEG and H.263. These operate by dividing up an image or video into sections or blocks, performing transforms on the data in the blocks, and compressing or coding the coefficients resulting from the transform.

The JPEG standard, for example, operates by dividing an image into 8x8 blocks of pixels (i.e., each block is an array of 64 pixels: 8 pixels in height and 8 pixels in width). A mathematical transform known as the "discrete cosine transform (DCT)" is calculated for each block in the image to produce a data set of coefficients.

A variable length code-based compression technique is then used to compress the data set and store the compressed data stream in an output file. The output file can then be decompressed to recover the DCT coefficients, the inverse DCT transform calculated, and the resulting blocks of pixels displayed to represent the original form of the image.

Mathematically, the DCT transforms the blocks of pixels from the spatial representation to the frequency representation. In the frequency representation, the image or video information can be divided into frequency components, some of which are more important than others. The compression algorithm selectively quantizes or discards the frequency components that do not adversely affect the reconstructed picture contents. In this manner, compression is achieved.

From a statistical signal processing standpoint, the DCT is a robust approximation to the optimal discrete-time *Karhunen-Loève transform* (KLT) of a first-order Gauss-Markov process with a positive correlation coefficient ρ when $\rho \rightarrow 1$. The KLT is optimal in the sense that it provides the most accurate representation of a signal by producing transform coefficients that are the eigen values of the input's autocorrelation matrix, and as known in the art, the eigen values are the optimum achievable result. In other words, the KLT is optimal in the energy compaction sense, i.e., among unitary transforms, the KLT packs signal energy into the fewest number of coefficients. However, the KLT is signal-dependent, therefore, it is

computationally complex and expensive to implement. The DCT has proven to be a much better alternative in practice in that it is signal independent, has linear phase, has real coefficients, and can be implemented using fast algorithms.

The DCT coefficients, X[0] through X[M-1], of an M x M transform (i.e., a transform having M^2 individual signal samples at its input to be processed row by row as M basis functions) and the input image pixels, x[0] through x[M-1], are related by the following equations:

$$X[m] = \alpha_m \sum_{n=0}^{M-1} x[n] \cos\left[\frac{\pi m}{2M}(2n+1)\right], \quad 0 \le m \le M-1,$$

with

$$\alpha_m = \begin{cases} \sqrt{1/M}, & m = 0 \\ \sqrt{2/M}, & 1 \le m \le M-1. \end{cases}$$

It has a closed-form expression and it is orthogonal. Orthogonality is desirable in a transform inasmuch as there is no redundancy among the M transform bases (e.g.,

they are orthogonal to each other). In the matrix format, we can represent the transformation of an input, x, to a transform coefficient, X, as X = Px, and the reconstruction of the transform coefficient back into the input x as x = P^TX, where P is the DCT transform matrix and P^T is its inverse transform matrix. Exploiting the symmetry of the coefficients cos $[(\pi m/2M)(2n + 1)]$ in the equation above, the functions performed by the DCT transform matrix P can be represented by a series of ±1 butterflies 12 and rotation angles 14, as illustrated in Fig. 1. The ±1 butterflies are a series of crossings which process one pair of inputs at a time (i.e., x[0] through x[7]) by adding and subtracting the inputs in pairs. For example, the first butterfly encountered by the data set x[0] through x[7] shown in Fig. 1 operates on the data pair x[0], x[7]. In the top branch of the first butterfly, the term x[0] is added to the term x[7], while in the bottom branch, the term x[7] is subtracted from x[0]. Similarly, in the second butterfly, the term x[1] is added to the term x[6], while in the bottom branch the term x[6] is subtracted from x[1]. In an 8 x 8 transform, the DCT initially performs four such butterflies (i.e., crossings) for a total of four discrete addition operations and four discrete subtraction operations. The DCT rotation angles are a series of multiplication operations carried out on the results achieved by the ±1 butterflies. As depicted in Fig. 1, "C π/4" signifies a multiplication operation (i.e., multiplying an input by cosine π/4). Similarly, "S π/4" signifies a multiplication operation (i.e., multiplying an input by sine π/4). This process results in a fast DCT

implementation. Using this method, eight DCT coefficients $X[0] - X[7]$ can be computed using 13 multiplication operations and 29 addition operations.

Despite all of the above advantages of the DCT, there is still room for improvement. For example, the DCT is a floating-point transform, i.e., the *cos* and *sin* multipliers in the 5 rotation angles $\{\pi/4, 3\pi/8, \pi/4, 7\pi/16, 3\pi/16\}$ are real numbers with infinite precision. Hence, the DCT cannot map integers to integers losslessly inasmuch as the product of the inputs, as processed by the ±1 butterflies, and the DCT rotation angles result in floating-point outputs that cannot be represented in binary form without truncation, thereby resulting in the loss of input data. More importantly, floating-point implementations are relatively slow, require too much hardware space, and consume too much power.

To combat these problems, most implementations of the DCT are based on integer arithmetic by scaling up the floating-point multipliers by very large factors (e.g., multiplying by a factor of 1000 or greater to rid the calculation of floating decimal points). Unfortunately, however, this ad-hoc approximation method still has problems; for instance, it does not reduce the complexity of the circuit and it still has truncation errors. Moreover, if more computational accuracy is needed, the scaling factors must be very large, thereby adding more complexity to the implementation.

SUMMARY OF THE INVENTION

A preferred embodiment of the invention provides an M × M multiplierless perfect reconstruction block transform (i.e., perfect reconstruction is realized if the invention is utilized for both analysis and synthesis, otherwise, if the invention is used on only one end, near-perfect reconstruction results) with symmetric/antisymmetric basis functions, i.e., linear phase filters. In a preferred embodiment, a cascade of ±1 butterfly stages is provided followed by two invertible matrices. Each invertible matrix is made up of a cascade of lifting steps and scaling factors (α_i). The scaling factors can be folded into the quantization stepsizes. A forward binDCT (e.g., for signal analysis), can be implemented using a cascade of ±1 butterflies and dyadic lifting steps. Furthermore, an inverse binDCT (e.g., for signal synthesis) can be easily realized using lifting steps of reverse order and inverted polarity, cascaded with ±1 butterflies.

In accordance with an embodiment of the invention, all of the lifting coefficients have been chosen to be dyadic rational numbers. Each dyadic lifting step can be constructed by a simple combination of shift-and-add operations.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other advantages, features, and applications of the invention will be apparent from the following detailed description of the invention which is provided in connection with the accompanying drawings in which:

Fig. 1 is a signal flow graph which depicts a conventional fast implementation of an 8 x 8 floating-point DCT;

Figs. 2(a)-2(c) are signal flow graphs which depict variations on lifting steps used in the analysis and synthesis of data samples;

Fig. 3 is a signal flow graph which depicts a general solution in accordance with the invention for a perfect reconstruction block transform whose basis functions have linear phase;

Fig. 4 is a signal flow graph which depicts how an invertible matrix U can be decomposed into a cascade of lifting steps and scaling factors (α_i) in accordance with a preferred embodiment of the invention;

Figs. 5-11 depict a forward binDCT in accordance with preferred embodiments of the invention;

Fig. 12 depicts frequency responses of a binDCT in accordance with a preferred embodiment of the invention;

Fig. 13 depicts a transform and inverse transform matrix of the first embodiment of a binDCT;

Fig. 14 depicts peak signal-to-noise ratios (PSNR) realized for two embodiments of the binDCT; and

Fig. 15 depicts a simplified block diagram of a transmission system incorporating analysis and synthesis filters which employ a binDCT block transform in accordance with preferred embodiments of the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Preferred embodiments and applications of the invention will now be described with reference to Figs. 2-15. Other embodiments may be realized and structural or logical changes may be made to the disclosed embodiments without departing from the spirit or scope of the invention. Although the invention is particularly described as applied to the analysis and synthesis of image and video data samples, it should be readily apparent that the invention may be applied to any other data samples or sets having the same or similar problems.

Instead of factoring the DCT into a cascade of rotation angles, as in conventional practice in the art, the invention utilizes a series of lifting steps (also known as "shear" operations or "ladder" structures). The basic principle behind a lifting step is demonstrated in the signal flow graphs depicted in Figs. 2(a)-2(c). In accordance with a preferred embodiment of the invention, the denominator of the lifting coefficient l_i is deliberately chosen to be dyadic in that it is a power of 2 (i.e., a rational number that can be written in the form of $1/2^m$, $k, m \in Z$) for easy binary implementation. Fig. 2(b) shows that the lifting step can achieve perfect reconstruction of a signal even with the presence of a nonlinear truncation operator such as a "*floor*" (which rounds down to the nearest integer), a "*round*" (which rounds either up or down to the nearest integer), or a "*ceiling*" (which rounds up to

the nearest integer). Fig. 2(c) illustrates how this property is exploited to implement the lifting step very efficiently using a combination of addition operations and bit-shift operations. The method is always feasible as long as the lifting coefficient is dyadic. For example, a lifting coefficient of 3/8 signifies "multiplying" an input value by 3 followed by a "division" by 8 implemented by a right-shift of 3 binary places (i.e., $2^3 = 8$ in the denominator). It should be noted that the term "multiplying" is actually inaccurate since a series of bit-shift and addition operations are performed upon the signal to achieve the same result without performing the actual multiplication operation.

As known in the art, binary multiplication may be simplified through a series of bit-shift and addition operations. Generally, in order to implement a multiplication operation, a multiplicand (i.e., a number that is to be multiplied by another) is multiplied by a multiplier (i.e., a number by which a multiplicand is to be multiplied). When multiplying binary numbers, bit-shift and addition operations may be implemented to effectively perform a multiplication without the same level of complexity required for multiplication.

A general description of binary bit-shift and addition operations, as substitutes for multiplication is found in U.S. Patent No. 3,691,359 to Dell et al., which is incorporated herein by reference.

For example, the numerator 3 of the lifting coefficient 3/8 signifies performing the following steps: a) a left-shift of 1 binary place upon the input signal to the lifting step; and b) after a left-shift of one place is performed (e.g., the decimal value 5 is represented as 101 in binary; after a left-shift, 101 becomes 1010), the result is then added to the original value of the input signal (e.g., 101), resulting in a lifting step output of 1111 binary (or decimal value 15). A multiplication by 3 has just been performed with just one bit-shift and one addition operation. In accordance with a preferred embodiment of the invention, each of the DCT's rotation angles (e.g., 14 of Fig. 1) are replaced with a minimal number of dyadic lifting steps, yet the resulting transform still retains most of the DCT's superior performance.

The DCT and the novel transformation referenced herein as "binDCT" are both M x M block transforms. For purposes of illustration only, an 8 x 8 block will be described herein. At the forward transform in the encoder, 8 input samples x[0] – x[7] are processed at a time, yielding 8 transform coefficients X[0] – X[7] that can then be quantized and encoded (e.g., entropy encoded) in a manner known in the art. In the decoder, the 8 encoded transform coefficients are entropy decoded, inverse quantized, and then fed to the inverse transform module. For 1D signals such as speech and audio, the input stream can be divided into 8-sample segments, each is then processed independently. For 2D and 3D signals (images and videos respectively), the input can be segmented into non-overlapped 8 x 8 blocks or 8 x 8 x

8 cubes. Each block or cube can be processed independently in separable fashion. For example, the 1D transformation can be applied to every row, then to every column, to obtain a 2D transformation.

As depicted in Figs. 5-8, each of which depicts a preferred embodiment of the invention, the 8 input samples labeled from $x[0]$ to $x[7]$ are first processed in four pairs of two by the ±1 butterflies 12. Each of the four ±1 butterflies 12 takes a pair of data samples and computes their sum as well as their difference.

As depicted in Fig. 3, each of the resulting sums may be arranged in the 4 upper branches U1, U2, U3, U4, which will be processed by invertible matrix U to produce the 4 even-indexed transform coefficients X[0], X[2], X[4], X[6] associated with the transform's 4 symmetric basis functions. Likewise, all of the resulting differences are fed into the 4 lower branches V1, V2, V3, V4, that will be further transformed by invertible matrix V to produce the 4 odd-indexed transform coefficients X[1], X[3], X[5], X[7] associated with the transform's 4 antisymmetric basis functions.

In accordance with an embodiment of the invention, the outputs of the butterflies are processed significantly different by the binDCT, as compared with the DCT. For instance, whereas the DCT relies on rotation angles (e.g., 14 of Fig. 1) which are depicted below in matrix form as

$$\begin{bmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{bmatrix} \ or \ \begin{bmatrix} \cos\theta_i & \sin\theta_i \\ \sin\theta_i & -\cos\theta_i \end{bmatrix},$$

the binDCT, in accordance with a preferred embodiment of the invention, relies on lifting steps, or cascades of shears (e.g., 16 of Figs. 5-8), a general matrix representation of which (to be described more fully below) is depicted below as

$$\begin{bmatrix} 1 & l_i \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ l_{i+1} & 1 \end{bmatrix}.$$

Since a rotation angle is orthogonal, its inverse is simply its transpose, e.g.,

$$\begin{bmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{bmatrix}^T \begin{bmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{bmatrix} = \begin{bmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{bmatrix} \begin{bmatrix} \cos\theta_i & -\sin\theta_i \\ \sin\theta_i & \cos\theta_i \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

Inverting a lifting step is achieved simply by inverting its polarity, i.e.,

$$\begin{bmatrix} 1 & -l_i \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & l_i \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \text{ or } \begin{bmatrix} 1 & 0 \\ -l_{i+1} & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ l_{i+1} & 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

This is always true as long as the diagonal elements of the matrix are unity with the same polarity (both +1 or −1). In the case that the diagonal elements have opposite polarity, the inverse of the lifting step is simply itself, i.e.,

$$\begin{bmatrix} \pm 1 & l_i \\ 0 & \mp 1 \end{bmatrix} \begin{bmatrix} \pm 1 & l_i \\ 0 & \mp 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

Therefore, transforms constructed from series of lifting steps are still perfectly invertible. Since the multiplication operations associated with the DCT rotation angles require floating-point arithmetic, and since it is very difficult to choose rotation angles that yield integer multiplications, in accordance with a preferred embodiment of the invention, the orthogonality associated with the DCT may be sacrificed in the binDCT in favor of lower complexity. Specifically, lifting steps are used to replace the DCT's rotation angles, preferably having the denominator of the lifting coefficients l_i chosen to be dyadic, both the forward and the inverse transform can be implemented without using any multiplication (or division) arithmetic operations, particularly floating point multiplication. Fig. 9 depicts an embodiment

of an inverse binDCT which employs inverted lifting steps having dyadic lifting coefficients.

In accordance with another aspect of the invention, specific choices of lifting coefficients l_i were made to result in high-performance transforms.

In each of the 4 upper branches of the binDCTs depicted within Figs. 5-8, the DCT's 2 butterflies (12a as in Fig. 1) are retained; however, the two upper branch DCT rotation angles of $\pi/4$ and $3\pi/8$ can be replaced with one of the following sets of lifting steps depicted below in matrix form.

$$\frac{\pi}{4}: \begin{bmatrix} 1 & 0 \\ 1/2 & -1 \end{bmatrix} \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 1 & -1/2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 1 & -1 \end{bmatrix}, \text{ or } \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

For example, the upper branch DCT rotation angle of $\pi/4$ (14a as seen in Fig. 1) is replaced with a pair of lifting steps 16a (of Figs. 5-8). For illustrative purposes, consider an input A on the upper branch of the first lifting step of 16a and an input of B on the lower branch of the first lifting step of 16a. Consequently, the output on the upper branch of the first lifting step is A+B and the output on the lower branch of the first lifting step is B. Similarly, the input on the lower branch of the second lifting step is B and the input for the upper branch of the second lifting step is A+B. Consequently, the output for the upper branch of the second lifting step is A+B and the output for the lower branch of the second lifting step is ½(A+B)-B. In accordance with a preferred embodiment of the invention, these lifting steps

can be implemented in software and/or hardware using a series of binary shifts and adds on the input data to produce the appropriate transform coefficients (e.g., X[0]...X[7]) representative of the original image data samples.

While any one of the above 3 matrix sets (or other equivalent sets apparent to those of ordinary skill in the art) may be employed to obtain these output results (albeit, with differing levels of accuracy), the first matrix set set forth above will be derived, by way of example, as a replacement for the upper branch $\pi/4$ rotation angle in Fig. 1.

One way in which respective outputs of A+B and B for the upper and lower branches of the first lifting step may be obtained is to multiply the input vector

$$\begin{bmatrix} A \\ B \end{bmatrix}$$

by a matrix which represents the first lifting step of 16a:

$$\begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}.$$

Performing matrix multiplication results in the respective upper and lower branch outputs of A+B and B in the first lifting step.

One way in which respective outputs of A+B and ½(A+B)-B for the upper and lower branches of the second lifting step of 16a may be obtained is to multiply the vector input to the second lifting step

$$\begin{bmatrix} A+B \\ B \end{bmatrix}$$

by a matrix which represents the second lifting step of 16a:

$$\begin{bmatrix} 1 & 0 \\ 1/2 & -1 \end{bmatrix}.$$

Using a method similar to that described above for the upper branch DCT rotation angle of $\pi/4$ in the graph of Fig. 1, the upper branch DCT rotation angle of $3\pi/8$ (14b in Fig. 1) may be replaced with the following sets of lifting steps (or equivalent lifting steps apparent to those skilled in the art) depicted below in matrix form:

$$\frac{3\pi}{8}: \begin{bmatrix} 1 & 0 \\ 3/8 & 1 \end{bmatrix} \begin{bmatrix} 1 & -3/8 \\ 0 & 1 \end{bmatrix}, \text{ or } \begin{bmatrix} 1 & 0 \\ -5/8 & 1 \end{bmatrix} \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -5/8 & 1 \end{bmatrix}.$$

In each of the 4 lower branches of the binDCTs, depicted within Figs. 5-8, which yield the odd-indexed transform coefficients (i.e., X[1], X[3], X[5], X[7]), three DCT rotation angles (i.e., $\pi/4$ (14d), $7\pi/16$ (14e), and $3\pi/16$ (14f, as shown in Fig. 1) are also replaced with lifting steps, particularly those lifting steps having dyadic denominators in their lifting coefficients. It should be noted that special care must be taken in choosing a lifting coefficient to replace rotation angle $\pi/4$ (14d) in the lower branches since it precedes the remaining angles in the structure. The following choices of lifting steps (depicted in matrix form) are preferable to yield better coding performances although other equivalent lifting steps may be apparent to those skilled in the art:

$$\frac{\pi}{4}: \begin{bmatrix} -1 & 5/8 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 3/8 & 1 \end{bmatrix}, \begin{bmatrix} -1 & 3/8 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 11/16 & 1 \end{bmatrix} \begin{bmatrix} 1 & -7/16 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} -1 & 7/16 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 3/4 & 1 \end{bmatrix} \begin{bmatrix} 1 & -7/16 \\ 0 & 1 \end{bmatrix},$$

$$\begin{bmatrix} -1 & 1/2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 3/4 & 1 \end{bmatrix} \begin{bmatrix} 1 & -1/2 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} -1 & 3/8 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 3/4 & 1 \end{bmatrix} \begin{bmatrix} 1 & -3/8 \\ 0 & 1 \end{bmatrix}, \text{ or } \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}.$$

Next, the DCT rotation angle $7\pi/16$ (14e shown in Fig. 1) may be replaced with one of the following sets of lifting steps (or equivalent steps) depicted below in matrix form:

$$\frac{7\pi}{16}: \begin{bmatrix} 1 & -1/8 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 3/16 & 1 \end{bmatrix}\begin{bmatrix} 1 & -3/16 \\ 0 & 1 \end{bmatrix}, \text{ or } \begin{bmatrix} 1 & 0 \\ -13/16 & 1 \end{bmatrix}\begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ -13/16 & 1 \end{bmatrix}.$$

Finally, the DCT rotation angle $3\pi/16$ (14f shown in Fig. 1) may be replaced with one of the following sets of lifting steps (or equivalent steps) depicted below in matrix form:

$$\frac{3\pi}{16}: \begin{bmatrix} 1 & 0 \\ -1/2 & 1 \end{bmatrix}\begin{bmatrix} 1 & 7/8 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ -1/8 & 1 \end{bmatrix}\begin{bmatrix} 1 & 1/2 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ -3/4 & 1 \end{bmatrix}, \text{ or } \begin{bmatrix} 1 & 0 \\ -1/4 & 1 \end{bmatrix}\begin{bmatrix} 1 & 1/2 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ -1/4 & 1 \end{bmatrix}.$$

Note that each embodiment of the binDCT still employs the following ± 1 butterfly (of Fig. 1) which may be represented in matrix form as:

$$\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

and whose inverse is itself scaled down by a factor of two. To recover *x[i]* exactly on the synthesis end, the outputs of the inverse binDCTs have to be attenuated by ¼, which is preferably implemented in software and/or hardware as a right-shift of the data two binary places. It should be noted that in lossless coding, the ±1 butterfly is not very efficient since it amplifies the signal by 2. To compensate for this effect, in accordance with another aspect of the invention one or more ±1 butterflies (e.g., 12 in Figs. 5-8) may be replaced with either of the following sets of lifting steps (or equivalent steps) as depicted below in matrix form:

$$\begin{bmatrix} 1 & -1/2 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ 1 & -1 \end{bmatrix}, \text{ or } \begin{bmatrix} 1 & 0 \\ 1/2 & -1 \end{bmatrix}\begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}.$$

As an example, Figs. 10 and 11 are respectively provided to illustrate lossless versions of the embodiment of the binDCT shown in Fig. 5 and its inverse binDCT in which the ±1 butterflies (e.g., 12 of Fig. 5-8) are replaced with lifting steps having dyadic denominators in their lifting coefficients. Similar modifications may be made to each embodiment (e.g., as respectively depicted in Figs. 5-8) without departing from the spirit or scope of the invention.

Fig. 12 depicts a graphical representation of frequency response for a forward and inverse binDCT, respectively, in accordance with a preferred embodiment of the invention.

Fig. 13 illustrates a table of coefficients for a transform matrix which may be used to produce the same or substantially the same coefficients produced by binDCT, in accordance with embodiments of the invention (e.g., as in Fig. 5). The top portion of the chart 130 depicts transform coefficients used for signal analysis. The bottom portion of the chart 132 depicts transform coefficients used for signal synthesis. Each portion of the table 130, 132 is obtained by first converting each ±1 butterfly and each lifting step within binDCT, e.g., the preferred embodiment of the invention shown in Fig. 5, into matrix form. Next, multiplying each of the matrices within a basis function (e.g., x[0]) to respectively produce results in the 8 rows representative of the 8 output coefficients produced using binDCT. That is, the Fig. 13 table provides a matrix of transform coefficients, h_0 through h_7, which are M basis functions of an M x M transform consistent with a preferred embodiment of the invention.

Fig. 14 depicts a table showing empirical data of peak signal-to-noise ratios (PSNR) between reconstructed and original images. The table depicts results for three separate test images represented in 512 x 512 8-bit grayscale; "Lena," "Goldhill" and "Barbara." The table depicts the PSNR for the DCT in the left

column of each test image and offers a comparison with two preferred embodiments of the invention (of Figs. 5 and 7, respectively). As can be seen in Fig. 14, the performance of the binDCT is very similar to that of the DCT.

Referring now to Fig. 15, a transmission system is depicted in which each embodiment of the binDCT may be employed within a respective analysis block 150, 152, and each inverted binDCT may be employed within a respective synthesis block 154, 156. At the analysis side, an input signal Y(z) is processed by a pair of analysis block 150, 152, each employing an embodiment of the binDCT block transform in accordance with the invention. The resulting sub-band signals are then decimated by a factor of two. At the synthesis side, the signals $Y_0(z)$, $Y_1(z)$ are interpolated, and transformed by analysis blocks 154, 156, each of which employs an embodiment of the inverse binDCT block transform in accordance with the invention. The synthesized signals are then added to produce the output signal Y(z)'. As should be readily apparent, the application of the invention is not limited to a transmission system and may be employed for other applications including, but not limited to, storing the coded data and reproduction of the data using any given medium. Furthermore, although an 8 x 8 transform has been depicted, the implementation of the invention is not limited to 8 x 8 transforms and, accordingly, may be used to process matrices of any dimension without departing from the spirit or scope of the invention.

The invention provides a simplified block transform that can be implemented using only bit-shift and add operations. The transform replaces DCT rotation angles with a series of lifting steps preferably having dyadic denominators in their lifting coefficients specifically chosen to allow the binDCT to operate with substantially the same degree of accuracy as the DCT, but without the DCT's level of complexity. The result is a simpler, faster, transform process which retains all of the practical benefits of the DCT.

The novel block transform of the invention, "binDCT," offers at least the following advantages:

- The binDCT has a fast, elegant implementation utilizing only shift-and-add operations. No multiplication is needed. For example, eight transform coefficients can be computed using only 14 bit shift operations and 31 addition operations (13 floating point-multiplication operations and 29 addition operations are required for the DCT);

- The binDCT can map integers to integers with exact reconstruction. It also allows a unifying lossy/lossless coding framework;

- In software implementation, the binDCT is at least 3 – 4 times faster than the floating-point DCT. In hardware implementations, the binDCT may be approximately 10 times or more faster than the floating-point DCT;

- The multiplierless property of the binDCT allows efficient very large scale integrated circuit (VLSI) implementations in terms of both chip area and power consumption;

- The binDCT approximates the DCT very closely. Perceptual quantization matrices and coding strategies designed specifically for the DCT can be applied to the binDCT immediately without any complicated modification; and

- The cascade of a well-tuned forward binDCT followed by an inverse DCT (or a forward DCT followed by an inverse binDCT) produces a reasonable near-perfect-reconstruction system.

The binDCT provides very high coding performance. For instance, the coding gain (a popular measure of a transform's energy compaction property) of several binDCT versions may range in certain examples from 8.77 to 8.82 dB, whereas the DCT has a coding gain of 8.83 dB. In image coding experiments, the binDCT may be approximately 0.1 - 1.0 dB below the DCT in the signal-to-noise

ratios of the reconstructed images in certain examples. The binDCT may be found to offer higher visual reconstructed quality than the DCT.

While preferred embodiments of the invention have been described and illustrated, it should be apparent that many modifications can be made to the invention and the invention's application without departing from its spirit or scope. Accordingly, the invention is not limited by the foregoing description or drawings, but is only limited by the scope of the appended claims.

What is claimed is:

1. A method of processing digital samples, the method comprising:

processing the digital samples with a plurality of lifting steps, said act of processing being multiplierless.

2. The method as in claim 1 further comprising:

receiving at an input of a transform a plurality of sample segments of discrete time signals; and

generating a plurality of transform coefficients.

3. The method as in claim 2 further comprising processing the plurality of sample segments in pairs of two, said act of processing generating a plurality of sums and differences of said sample segments.

4. The method as in claim 1, wherein a lifting coefficient of the lifting steps is dyadic.

5. The method as in claim 3, wherein said act of processing is achieved with at least one ±1 butterfly.

6. The method as in claim 5, wherein said act of processing is achieved with a lifting step which, in matrix form, can be expressed as either:

$$\begin{bmatrix} 1 & -1/2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 1 & -1 \end{bmatrix}, \text{ or } \begin{bmatrix} 1 & 0 \\ 1/2 & -1 \end{bmatrix} \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}.$$

7. The method as in claim 1 further comprising:

receiving at an input of a transform a plurality of generated transform coefficients; and

generating a plurality of sample segments of discrete time signals.

8. The method as in claim 7 further comprising processing a plurality of sums and differences generated from said act of processing the digital samples with a plurality of ± 1 butterflies.

9. The method as in claim 8, wherein said act of processing a plurality of sums and differences is achieved with a plurality of lifting steps having dyadic lifting coefficients.

10. The method as in claim 2, wherein said act of receiving further comprises receiving at an input of an M x M transform M sample segments of discrete time signals.

11. The method as in claim 10, wherein said act of generating further comprises generating M transform coefficients.

12. The method as in claim 7, wherein said act of receiving further comprises receiving at an input of an inverse M x M transform M generated transform coefficients.

13. The method as in claim 12, wherein said act of generating further comprises generating M sample segments of discrete time signals.

14. The method as in claim 4, wherein one of the following sets of dyadic lifting coefficients, as represented in matrix form, is employed:

$$\begin{bmatrix} 1 & -1/2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 1 & -1 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 1/2 & -1 \end{bmatrix} \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}, \text{ or } \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}.$$

15. The method as in claim 4, wherein one of the following sets of dyadic lifting coefficients, as represented in matrix form, is employed:

$$\begin{bmatrix}1 & 0\\ 3/8 & 1\end{bmatrix}\begin{bmatrix}1 & -3/8\\ 0 & 1\end{bmatrix}, \text{ or } \begin{bmatrix}1 & 0\\ -5/8 & 1\end{bmatrix}\begin{bmatrix}1 & 1\\ 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\ -5/8 & 1\end{bmatrix}.$$

16. The method as in claim 4, wherein one of the following sets of dyadic lifting coefficients, as represented in matrix form, is employed:

$$\begin{bmatrix}-1 & 5/8\\ 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\ 3/8 & 1\end{bmatrix}, \begin{bmatrix}-1 & 3/8\\ 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\ 11/16 & 1\end{bmatrix}\begin{bmatrix}1 & -7/16\\ 0 & 1\end{bmatrix}, \begin{bmatrix}-1 & 7/16\\ 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\ 3/4 & 1\end{bmatrix}\begin{bmatrix}1 & -7/16\\ 0 & 1\end{bmatrix},$$
$$\begin{bmatrix}-1 & 1/2\\ 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\ 3/4 & 1\end{bmatrix}\begin{bmatrix}1 & -1/2\\ 0 & 1\end{bmatrix}, \begin{bmatrix}-1 & 3/8\\ 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\ 3/4 & 1\end{bmatrix}\begin{bmatrix}1 & -3/8\\ 0 & 1\end{bmatrix}, \text{ or } \begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}.$$

17. The method as in claim 4, wherein one of the following sets of dyadic lifting coefficients, as represented in matrix form, is employed:

$$\begin{bmatrix}1 & -1/8\\ 0 & 1\end{bmatrix}, \begin{bmatrix}1 & 0\\ 3/16 & 1\end{bmatrix}\begin{bmatrix}1 & -3/16\\ 0 & 1\end{bmatrix}, \text{ or } \begin{bmatrix}1 & 0\\ -13/16 & 1\end{bmatrix}\begin{bmatrix}1 & 1\\ 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\ -13/16 & 1\end{bmatrix}.$$

18. The method as in claim 4, wherein one of the following sets of dyadic lifting coefficients, as represented in matrix form, is employed:

$$\begin{bmatrix}1 & 0\\ -1/2 & 1\end{bmatrix}\begin{bmatrix}1 & 7/8\\ 0 & 1\end{bmatrix}, \begin{bmatrix}1 & 0\\ -1/8 & 1\end{bmatrix}\begin{bmatrix}1 & 1/2\\ 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\ -3/4 & 1\end{bmatrix}, \text{ or } \begin{bmatrix}1 & 0\\ -1/4 & 1\end{bmatrix}\begin{bmatrix}1 & 1/2\\ 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\ -1/4 & 1\end{bmatrix}.$$

19. An analysis filter, the filter comprising:

a receiver for receiving at an input a plurality of sample segments of discrete time signals; and

means for processing the plurality of sample segments of discrete time signals with a plurality of lifting steps, the processing being multiplierless, each of the plurality of lifting steps having a dyadic lifting coefficient, and the means for processing also being capable of generating a plurality of transform coefficients.

20. A synthesis filter, the filter comprising:

a receiver for receiving at an input a plurality of generated transform coefficients; and

means for processing the plurality of generated transform coefficients through a plurality of lifting steps, the processing being multiplierless, each of the plurality of lifting steps having a dyadic lifting coefficient, and said means for processing also being capable of generating a plurality of sample segments of discrete time signals.

21. A computer readable storage medium containing a computer readable code for operating a computer to process digital samples, said code causing said computer to:

process the digital samples with a plurality of lifting steps, said act of processing being multiplierless.

22. The computer readable storage medium of claim 21, wherein said code further causes said computer to:

receive at an input of a transform a plurality of sample segments of discrete time signals; and

generate a plurality of transform coefficients.

23. The computer readable storage medium method of claim 22, wherein said code further causes said computer to:

process the plurality of sample segments in pairs of two, thereby generating a plurality of sums and differences of said sample segments.

24. The computer readable storage medium of claim 21, wherein a lifting coefficient of the lifting steps is dyadic.

25. The computer readable storage medium of claim 23, wherein said code causes said act of processing to be achieved with at least one ±1 butterfly.

26. The computer readable storage medium of claim 25, wherein said act of processing is achieved with a lifting step which, in matrix form, can be expressed as either:

$$\begin{bmatrix} 1 & -1/2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 1 & -1 \end{bmatrix}, \text{ or } \begin{bmatrix} 1 & 0 \\ 1/2 & -1 \end{bmatrix} \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}.$$

27. The computer readable storage medium of claim 21, wherein said code further causes said computer to:

receive at an input of a transform a plurality of generated transform coefficients; and

generate a plurality of sample segments of discrete time signals.

28. The computer readable storage medium of claim 27, wherein said code further causes said computer to process a plurality of sums and differences generated from said act of processing the digital samples with a plurality of ±1 butterflies.

29. The computer readable storage medium of claim 28, wherein said code causes said act of processing a plurality of sums and differences to be achieved with a plurality of lifting steps having dyadic lifting coefficients.

30. The computer readable storage medium of claim 22, wherein said code further causes said computer to receive at an input of an M x M transform M sample segments of discrete time signals.

31. The computer readable storage medium of claim 30, wherein said code further causes said computer to generate M transform coefficients.

32. The computer readable storage medium of claim 27, wherein said code further causes said computer to receive at an input of an inverse M x M transform M generated transform coefficients.

33. The computer readable storage medium of claim 32, wherein said code further causes said computer to generate M sample segments of discrete time signals.

34. The computer readable storage medium of claim 24, wherein said code causes one of the following lifting coefficients, as represented in matrix form, to be employed:

$$\begin{bmatrix}1 & -1/2\\0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\1 & -1\end{bmatrix}, \begin{bmatrix}1 & 0\\1/2 & -1\end{bmatrix}\begin{bmatrix}1 & 1\\0 & 1\end{bmatrix}, \text{ or } \begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}.$$

35. The computer readable storage medium of claim 24, wherein said code causes one of the following lifting coefficients, as represented in matrix form, to be employed:

$$\begin{bmatrix}1 & 0\\3/8 & 1\end{bmatrix}\begin{bmatrix}1 & -3/8\\0 & 1\end{bmatrix}, \text{ or } \begin{bmatrix}1 & 0\\-5/8 & 1\end{bmatrix}\begin{bmatrix}1 & 1\\0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\-5/8 & 1\end{bmatrix}.$$

36. The computer readable storage medium of claim 24, wherein said code causes one of the following lifting coefficients, as represented in matrix form, to be employed:

$$\begin{bmatrix}-1 & 5/8\\0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\3/8 & 1\end{bmatrix}, \begin{bmatrix}-1 & 3/8\\0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\11/16 & 1\end{bmatrix}\begin{bmatrix}1 & -7/16\\0 & 1\end{bmatrix}, \begin{bmatrix}-1 & 7/16\\0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\3/4 & 1\end{bmatrix}\begin{bmatrix}1 & -7/16\\0 & 1\end{bmatrix}.$$

$$\begin{bmatrix}-1 & 1/2\\0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\3/4 & 1\end{bmatrix}\begin{bmatrix}1 & -1/2\\0 & 1\end{bmatrix}, \begin{bmatrix}-1 & 3/8\\0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\3/4 & 1\end{bmatrix}\begin{bmatrix}1 & -3/8\\0 & 1\end{bmatrix}, \text{ or } \begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}.$$

37. The computer readable storage medium of claim 24, wherein said code causes one of the following lifting coefficients, as represented in matrix form, to be employed:

$$\begin{bmatrix} 1 & -1/8 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 3/16 & 1 \end{bmatrix}\begin{bmatrix} 1 & -3/16 \\ 0 & 1 \end{bmatrix}, \text{ or } \begin{bmatrix} 1 & 0 \\ -13/16 & 1 \end{bmatrix}\begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ -13/16 & 1 \end{bmatrix}.$$

38. The computer readable storage medium of claim 24, wherein said code causes one of the following lifting coefficients, as represented in matrix form, to be employed:

$$\begin{bmatrix} 1 & 0 \\ -1/2 & 1 \end{bmatrix}\begin{bmatrix} 1 & 7/8 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ -1/8 & 1 \end{bmatrix}\begin{bmatrix} 1 & 1/2 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ -3/4 & 1 \end{bmatrix}, \text{ or } \begin{bmatrix} 1 & 0 \\ -1/4 & 1 \end{bmatrix}\begin{bmatrix} 1 & 1/2 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} 1 & 0 \\ -1/4 & 1 \end{bmatrix}.$$

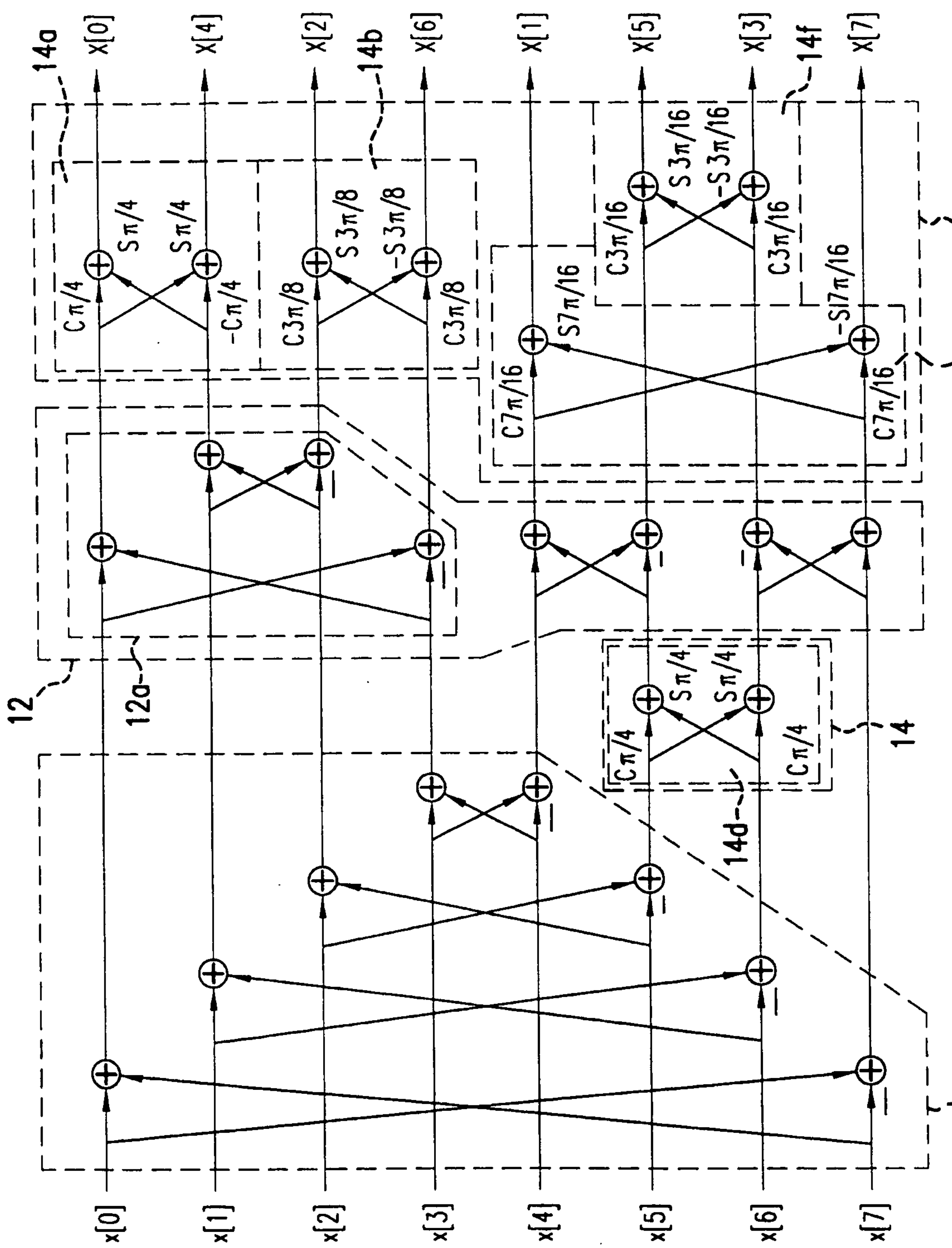

x[0]
x[1]
x[2]
x[3]
x[4]
x[5]
x[6]
x[7]
X[0]
X[4]
X[2]
X[6]
X[1]
X[5]
X[3]
X[7]
12
12a
14
14a
14b
14d
14e
14f
Cπ/4
Sπ/4
-Cπ/4
C3π/8
S3π/8
-S3π/8
C7π/16
S7π/16
-S7π/16
C3π/16
S3π/16
-S3π/16

FIG. 1

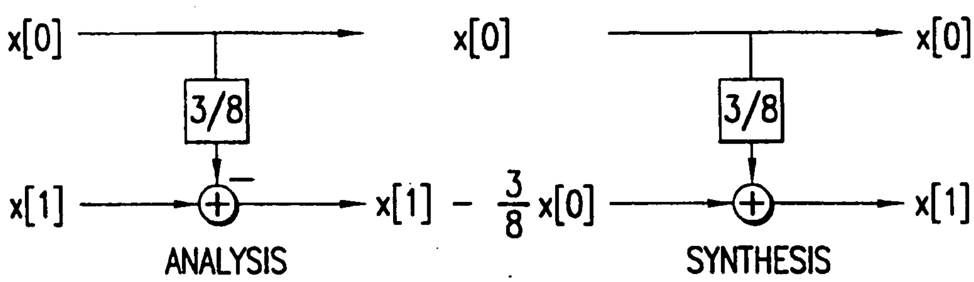


FIG.2(a)

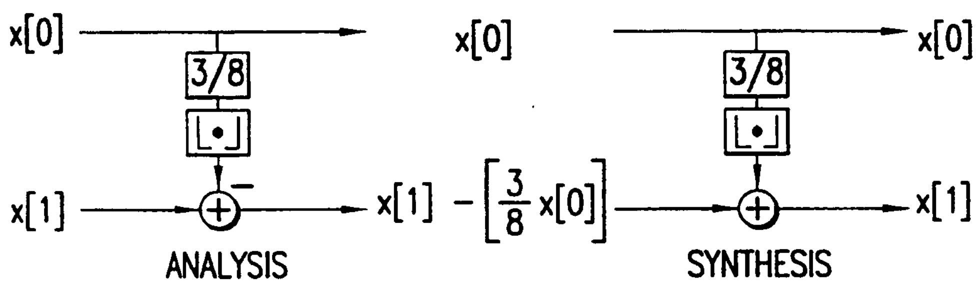


FIG.2(b)

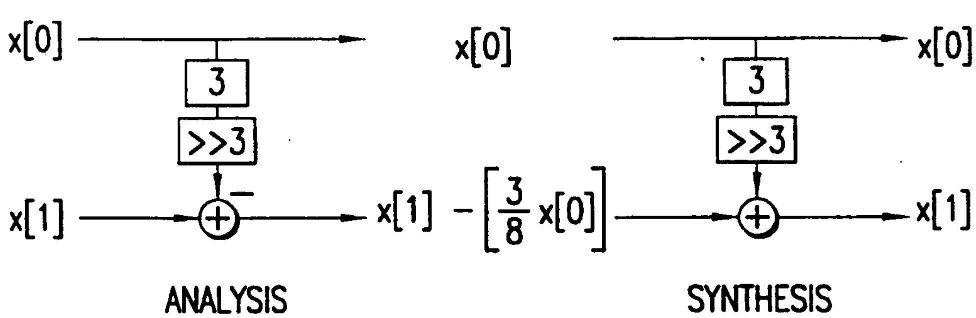


FIG.2(c)

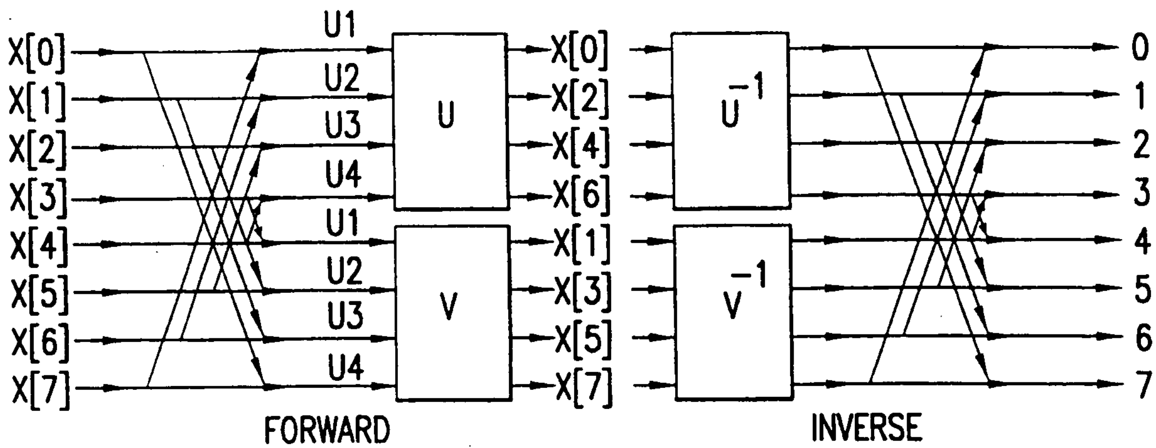

X[0]
X[1]
X[2]
X[3]
X[4]
X[5]
X[6]
X[7]
U1
U2
U3
U4
U1
U2
U3
U4
U
V
X[0]
X[2]
X[4]
X[6]
X[1]
X[3]
X[5]
X[7]
FORWARD
U^{-1}
V^{-1}
0
1
2
3
4
5
6
7
INVERSE

FIG.3

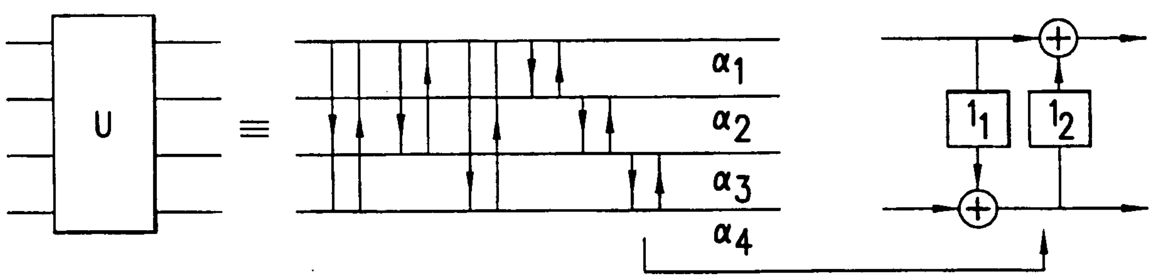

U
≡
α_1
α_2
α_3
α_4
l_1
l_2

FIG.4

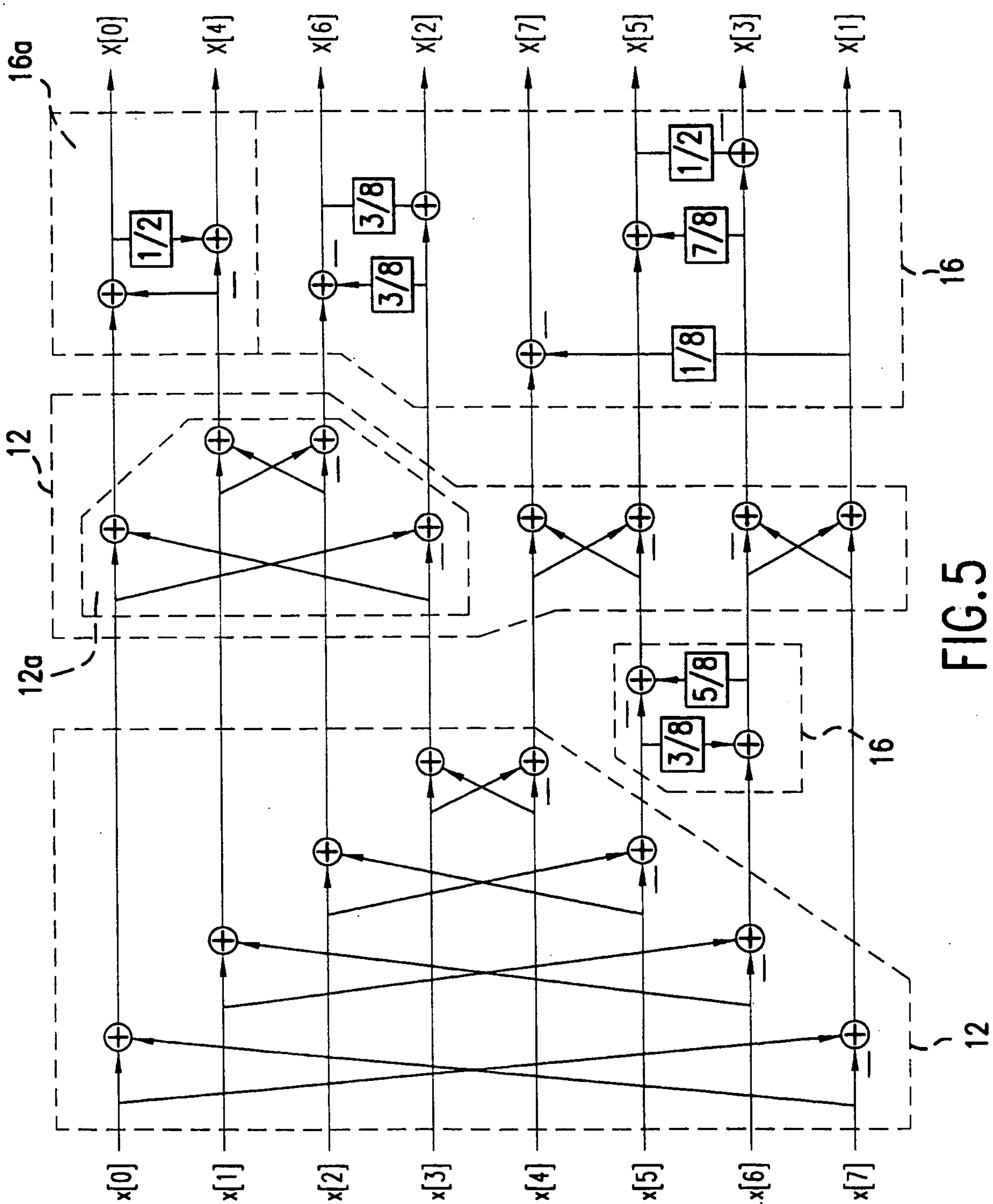

x[0]
x[1]
x[2]
x[3]
x[4]
x[5]
x[6]
x[7]
X[0]
X[4]
X[6]
X[2]
X[7]
X[5]
X[3]
X[1]
1/2
3/8
3/8
1/2
7/8
1/8
5/8
3/8
12
12a
16a
16
16
12

FIG.5

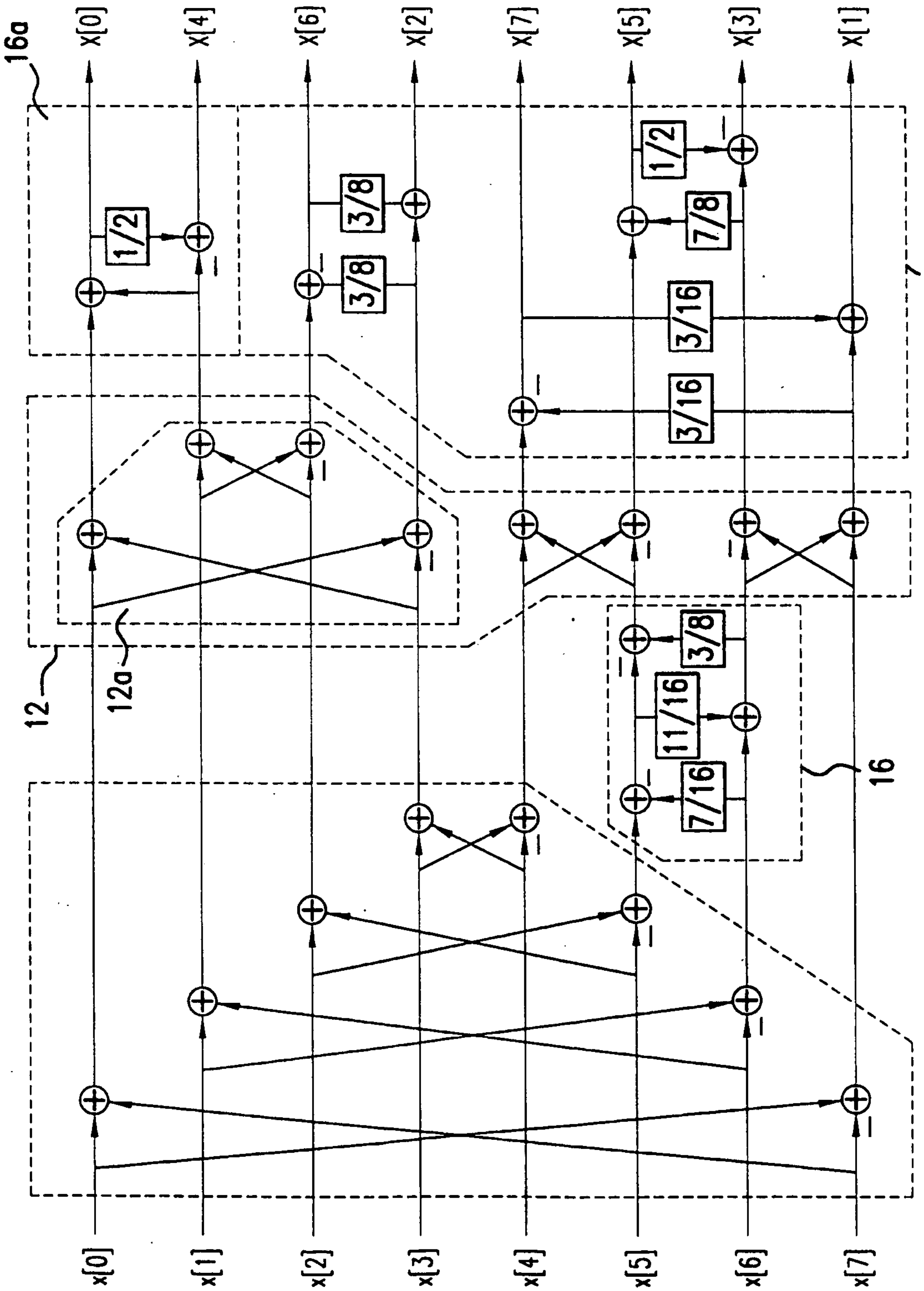

x[0]
x[1]
x[2]
x[3]
x[4]
x[5]
x[6]
x[7]
X[0]
X[4]
X[6]
X[2]
X[7]
X[5]
X[3]
X[1]
1/2
3/8
3/8
1/2
7/8
3/16
3/16
3/8
11/16
7/16
16a
16
12
12a
16

FIG.6

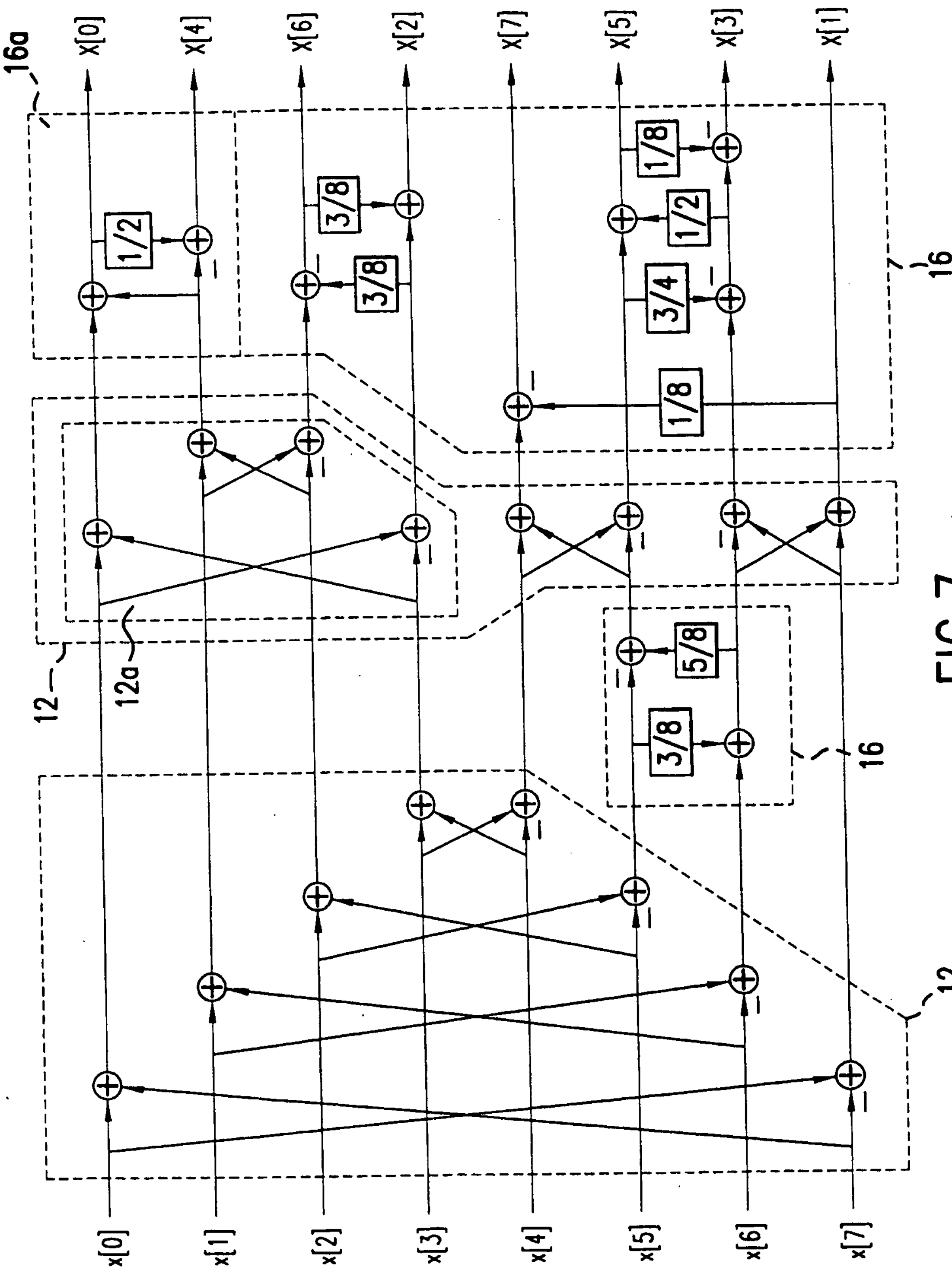

x[0]
x[1]
x[2]
x[3]
x[4]
x[5]
x[6]
x[7]
X[0]
X[4]
X[6]
X[2]
X[7]
X[5]
X[3]
X[1]
1/2
3/8
3/8
1/8
1/2
3/4
1/8
5/8
3/8
16a
16
16
12
12a
12

FIG.7

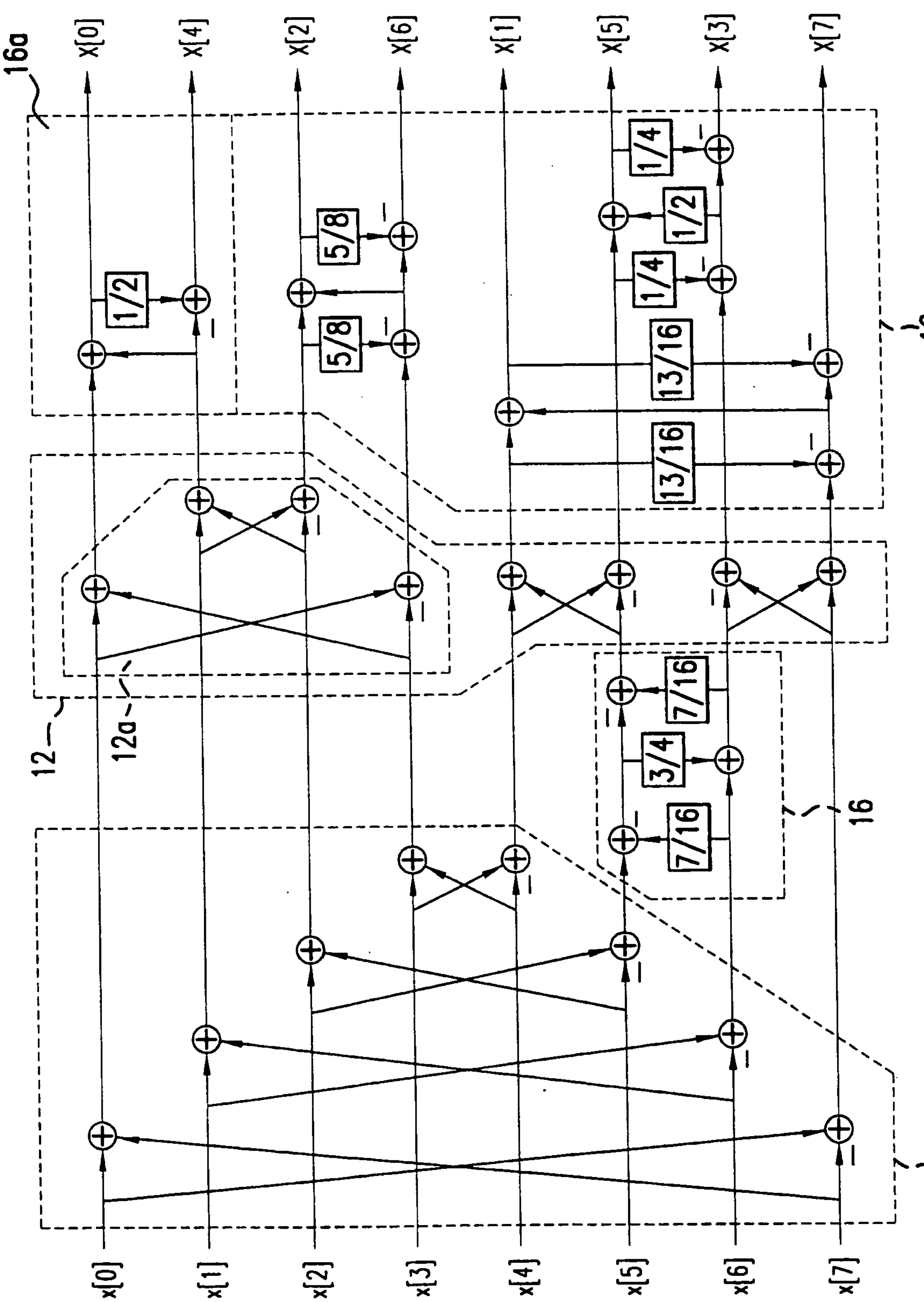

x[0]
x[1]
x[2]
x[3]
x[4]
x[5]
x[6]
x[7]
X[0]
X[4]
X[2]
X[6]
X[1]
X[5]
X[3]
X[7]
1/2
5/8
5/8
1/4
1/2
1/4
13/16
13/16
7/16
3/4
7/16
16a
12
12a
16
16
12

FIG.8

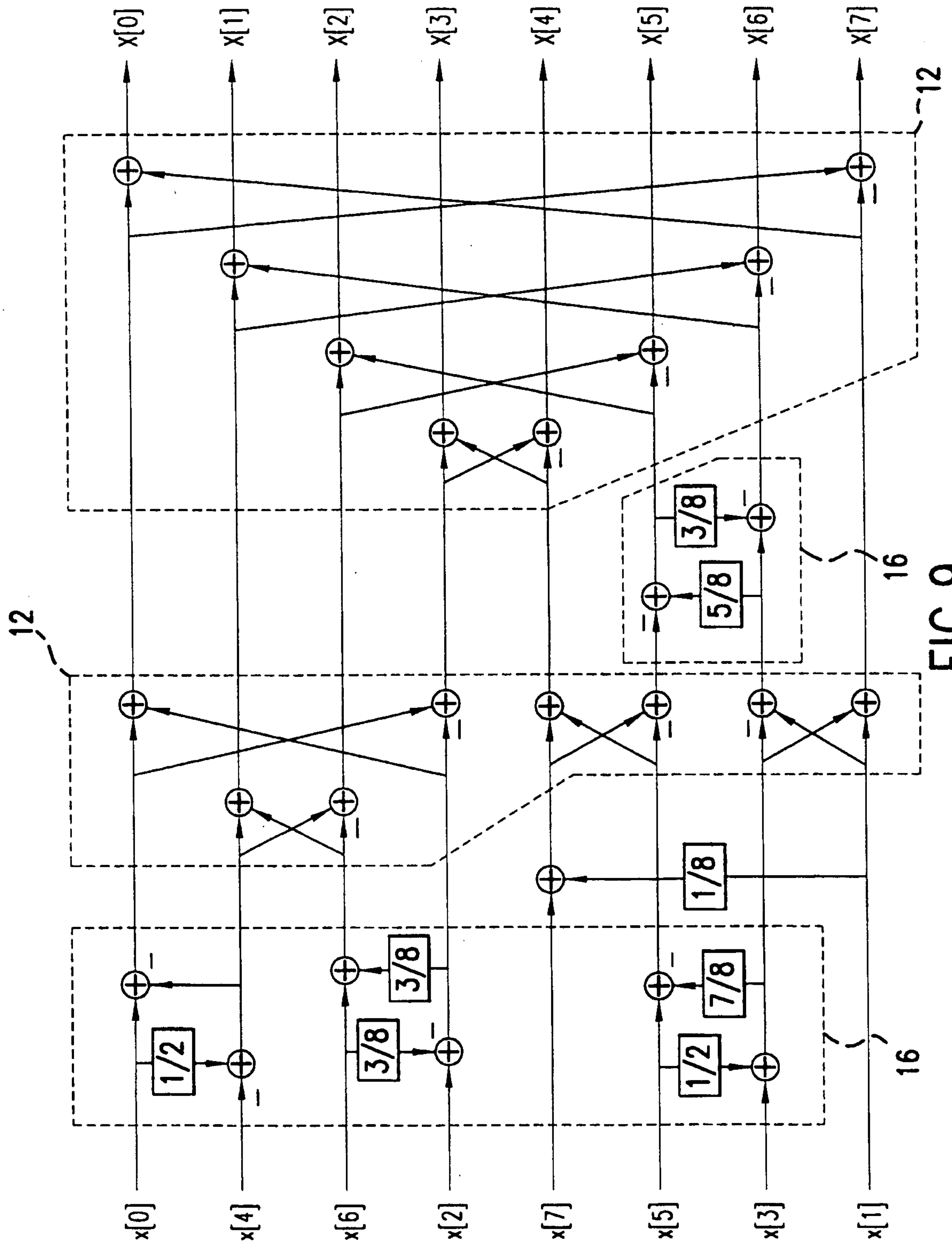

x[0]
x[4]
x[6]
x[2]
x[7]
x[5]
x[3]
x[1]
1/2
3/8
3/8
7/8
1/2
1/8
5/8
3/8
16
12
12
16
X[0]
X[1]
X[2]
X[3]
X[4]
X[5]
X[6]
X[7]

FIG.9

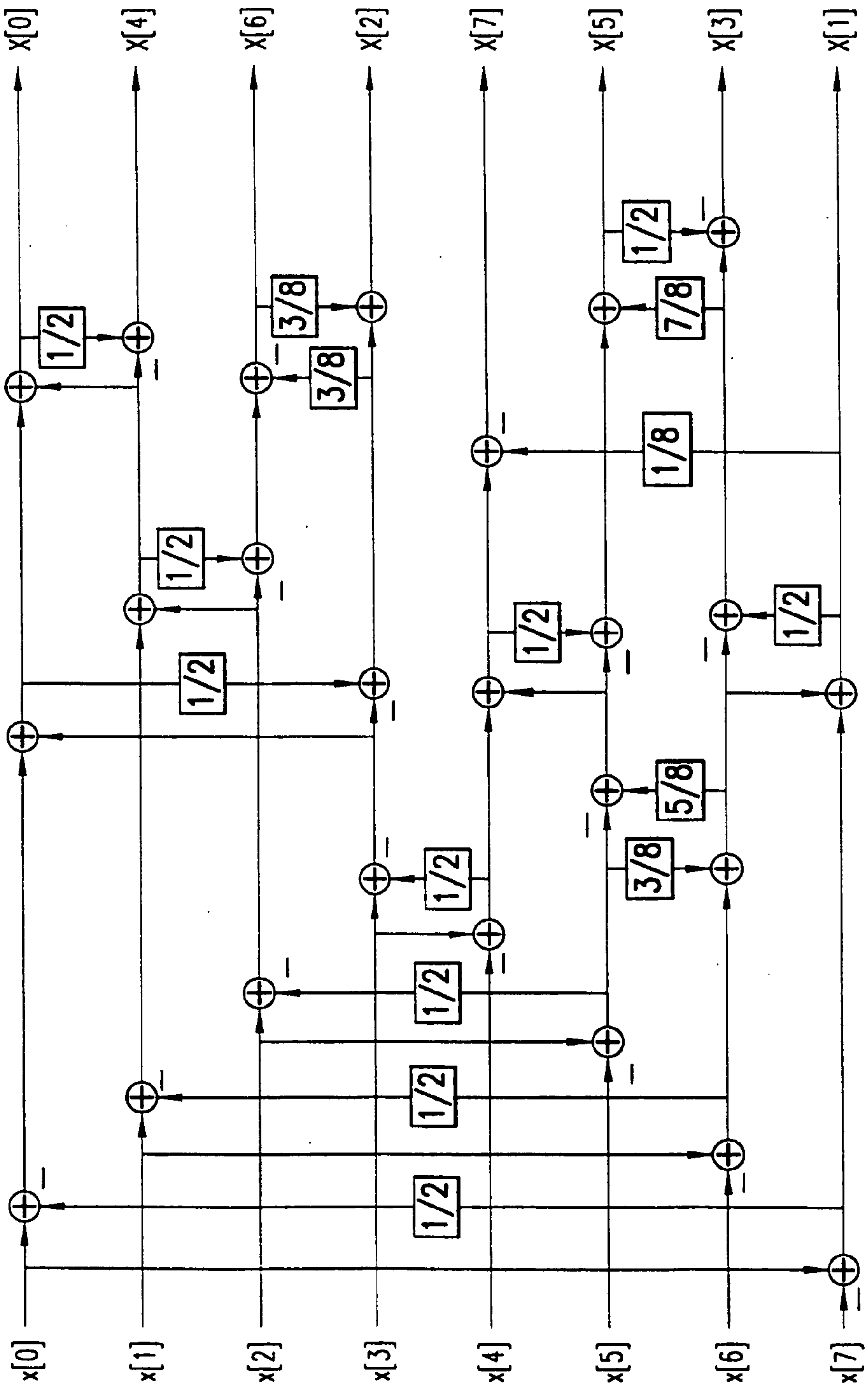

x[0]
x[1]
x[2]
x[3]
x[4]
x[5]
x[6]
x[7]
X[0]
X[4]
X[6]
X[2]
X[7]
X[5]
X[3]
X[1]
1/2
1/2
1/2
1/2
1/2
1/2
1/2
1/2
1/2
1/2
1/2
3/8
5/8
3/8
3/8
1/8
7/8
1/2

FIG.10

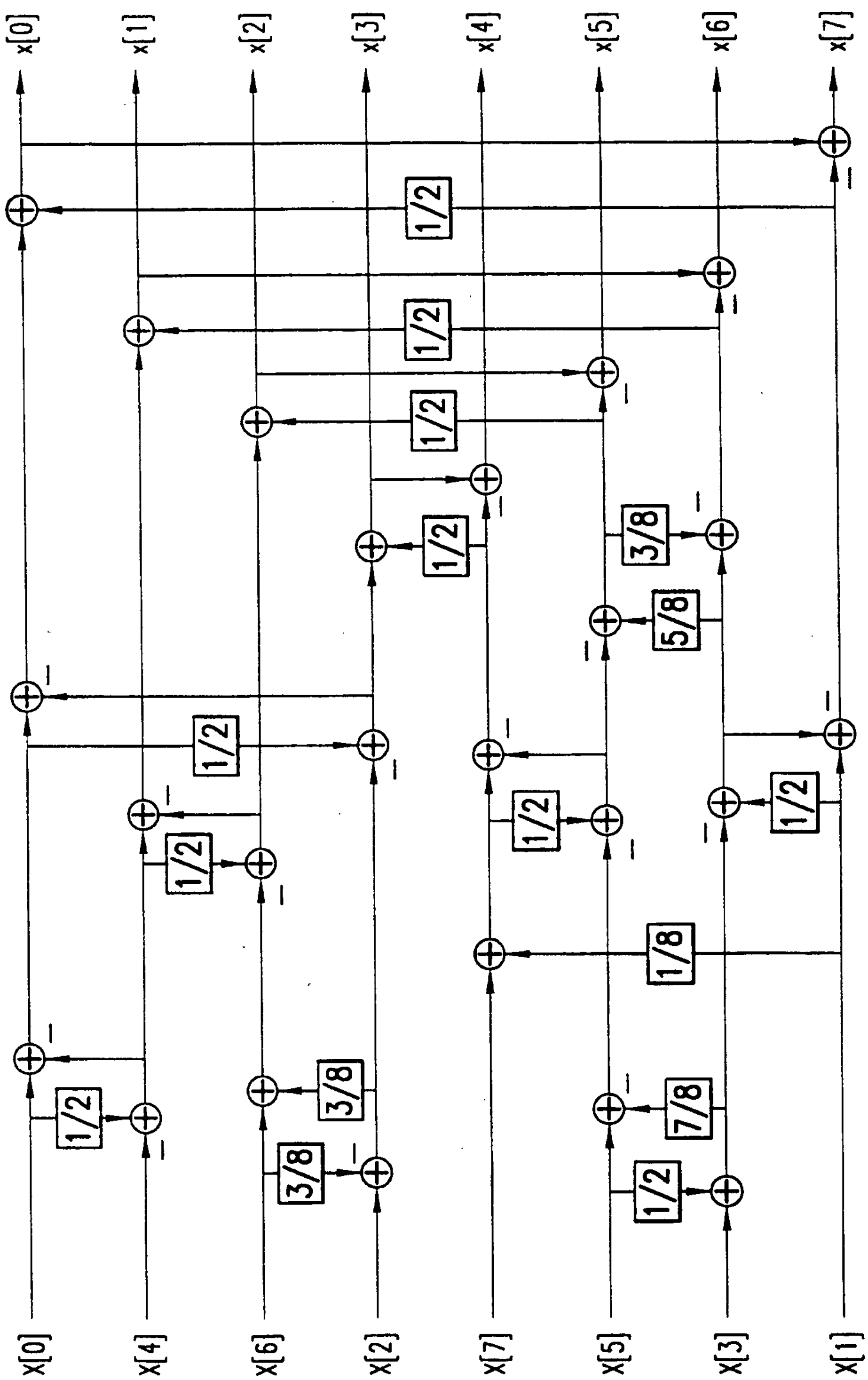


FIG. 11

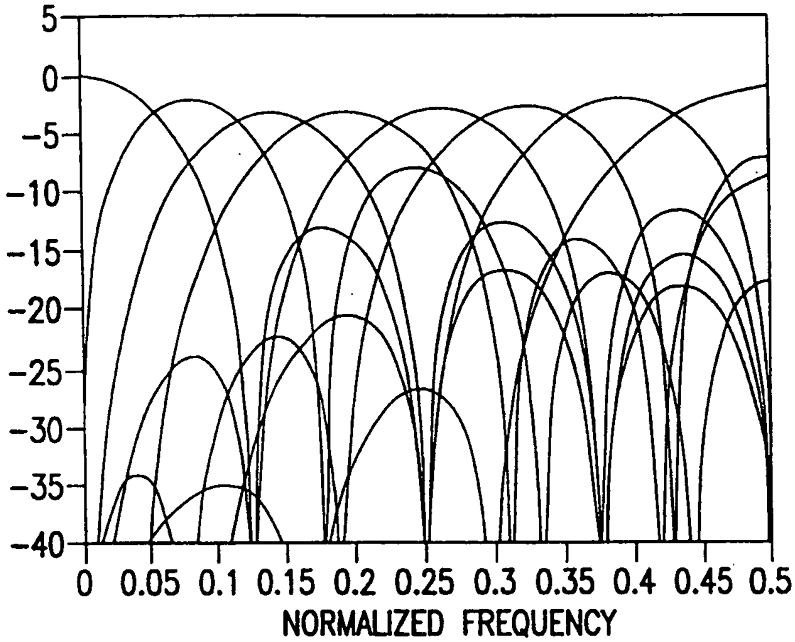


FIG.12A

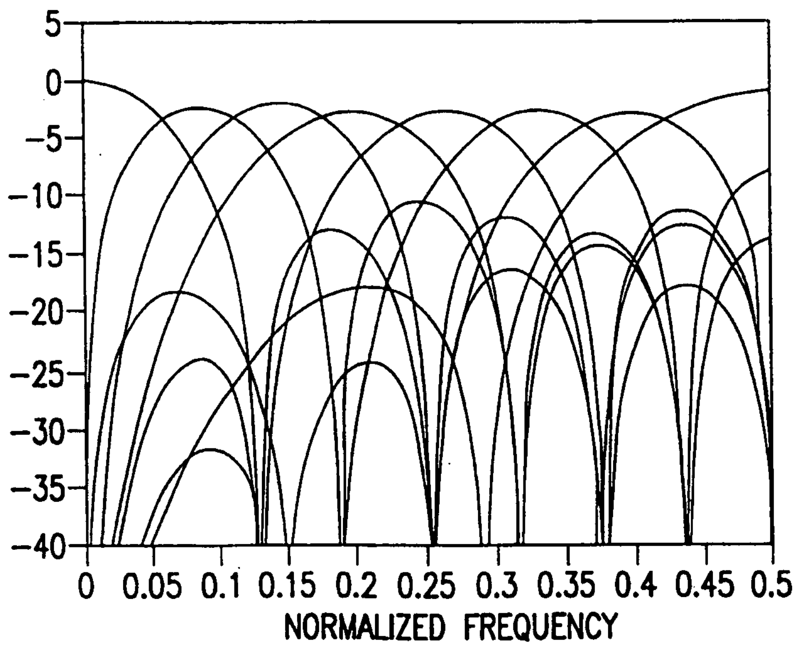


FIG.12B

130								
h_0	1/2	1/2	1/2	1/2	1/2	1/2	1/2	1/2
h_1	1/2	1/2	3/16	0	0	−3/16	−1/2	−1/2
h_2	55/128	3/16	−3/16	−55/128	−55/128	−3/16	3/16	55/128
h_3	9/32	−1/8	−19/64	−1/4	1/4	19/64	1/8	−9/32
h_4	1/4	−1/4	−1/4	1/4	1/4	−1/4	1/4	1/4
h_5	7/16	−3/4	7/32	1/2	−1/2	−7/32	3/4	−7/16
h_6	−3/16	1/2	−1/2	3/16	3/16	−1/2	1/2	−3/16
h_7	−1/16	1/4	−13/32	1/2	−1/2	13/32	−1/4	1/16
132								
g_0	1/4	1/4	1/4	1/4	1/4	1/4	1/4	1/4
g_1	1/2	13/32	1/4	1/16	−1/16	−1/4	−13/32	−1/2
g_2	1/2	3/16	−3/16	−1/2	−1/2	−3/16	3/16	1/2
g_3	1/2	−7/32	−3/4	−7/16	7/16	3/4	7/32	−1/2
g_4	1/2	−1/2	−1/2	1/2	1/2	−1/2	−1/2	1/2
g_5	1/4	−19/64	1/8	9/32	−9/32	−1/8	19/64	−1/4
g_6	−3/16	55/128	−55/128	3/16	3/16	−55/128	55/128	−3/16
g_7	0	3/16	−1/2	1/2	−1/2	1/2	−3/16	0

FIG.13

C RATIO	LENA			GOLDHILL			BABARA		
	DCT	binDCT-A	binDCT-C	DCT	binDCT-A	binDCT-C	DCT	binDCT-A	binDCT-C
LOSSLESS	-	4.540 bpp	4.522 bpp	-	5.063 bpp	5.042 bpp	-	4.990 bpp	4.982 bpp
1:8	39.91	39.11	39.44	36.25	35.65	35.82	36.31	35.48	35.71
1:16	36.38	35.61	36.02	32.76	32.34	32.45	31.11	30.19	30.67
1:32	32.90	32.37	32.74	30.07	29.81	29.87	27.28	26.57	26.90
1:64	29.67	29.51	29.61	27.93	27.75	27.79	24.58	24.23	24.24

FIG.14

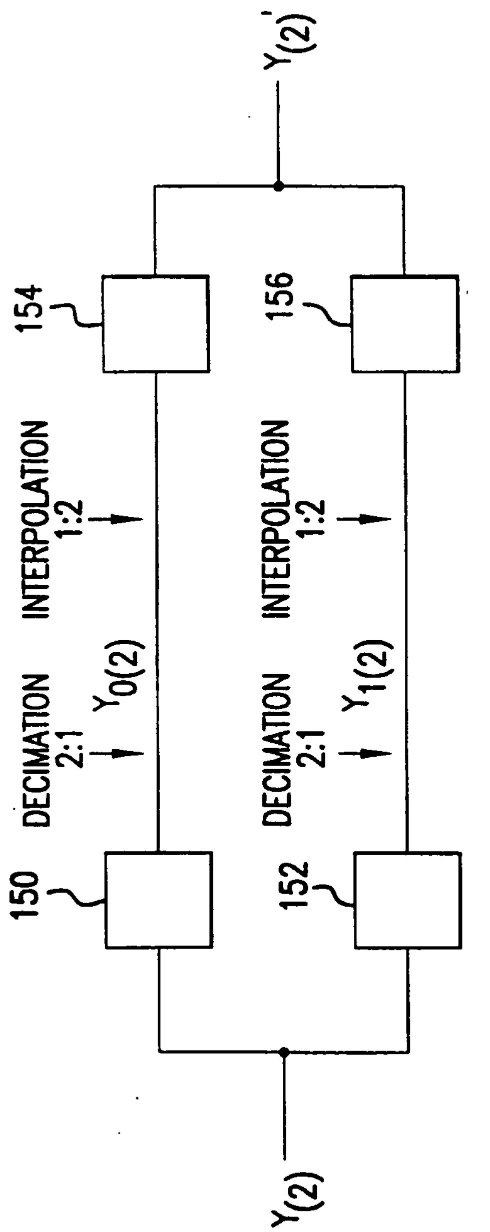

Y(2)'
154
156
INTERPOLATION 1:2
INTERPOLATION 1:2
DECIMATION 2:1
DECIMATION 2:1
Y0(2)
Y1(2)
150
152
Y(2)

FIG.15

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/06941

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :GO6F 17/14
US CL :708/402
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 708/402, 401, 400, 403

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,285,402 A (KEITH) 08 February 1994, abstract & Fig. 5	1-38
A	US 5,249,146 A (URAMOTO et al) 28 September 1993	1-38
A	US 5,642,438 A (BABKIN) 24 June 1997	1-38
A,P	US 5,999,958 A (CHEN et al) 07 December 1999	1-38
A.P	US 6,006,246 A (OHKI) 21 December 1999	1-38

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
24 MAY 2000	04 AUG 2000

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	DAVID H. MALZAHN James R. Matthews
Facsimile No. (703) 305-3230	Telephone No. (703) 305-9762